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A LOCAL DISTRIBUTION NETWORK USING THE PACKET RADIO TECHNOLOGY - A CASE STUDY

by

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ABSTRACT

The Packet Radio Communication Technology is receiving considerable attention for applications for which existing technologies are not suitable and as an economic solution for some applications for which existing technologies are applicable.

In this paper we present a preliminary design of a local distribution network using the Packet Radio technology and compare its cost with designs using a conventional technology.

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1. INTRODUCTION

In this paper we apply the Packet Radio (PR) Technology to a set of computers and terminals of the AUTODIN II network. The objective is to assess the applicability of the PR technology and to obtain a preliminary cost comparison between a conventional communication technology and the PR technology. The PR technology consists of interfacing radio devices to computers and terminals and using a broadcast radio channel for connecting the set of computers and terminals. The conventional technology used as a basis for comparision consists of concentrators and multiplexors for connecting low speed terminals and computers to a backbone network in a point-to-point configuration.

The Washington, D.C. area was used for the case study. The area covers a rectangle of approximately 80 by 100 miles and contains a set of 20 host computers and 109 terminals.

This case study is preliminary in several aspects. Firstly, the PR technology has not yet been extensively tested, and its devices have not been produced on a commerical basis. Therefore, the performance of the Packet Radio Network, PRNET, assumed in this study, is based on analytical results [Kleinrock, 1975; Gitman, 1975a] and extensive simulation studies of performance [Frank, 1975; NAC, 1976a]. The cost of communication devices is parametrized.

Secondly, computer programs have not yet been developed for PRNET design; hence, there is no claim of optimality or minimum cost design. However, the assumptions about the performance of the PR communication devices are stated, so that one can examine the impact of the various assumptions on the design and infer on cost changes when some of the assumptions are modified.

2. THE PACKET RADIO TECHNOLOGY

The PR technology was primarily developed to address communication requirements of applications for which the present conventional technology is not particularly suitable [Kahn, 1975], and to provide more efficient techniques for frequency spectrum utilization. However, it became apparent that this technology can compete with conventional technologies on an economic basis for certain types of applications. The PR technology is particularly suitable for applications in which:

a. Resources (e.g., terminals, computers) are mobile, so that a broadcast mode is necessary.

b. Resources are located in remote or hostile locations where hardwire connections are uneconomical or not feasible.

c. The traffic characteristics are of a bursty nature; that is, there is a high ratio of peak bandwidth to average bandwidth requirements.

The main features which distinguish the Packet Radio System from a point-to-point packet switching system (such as the ARPANET) are:

1. Devices in the system transmit packets by using a random access scheme, and

2. Devices broadcast so that packets can be transmitted to several devices simultaneously, and/or several packets can be simultaneously received by a

receiver because of independent transmissions of several devices. These features have a major impact on practically every aspect of network design.

The hardware of the PR technology is based on the Packet Radio Unit (PRU), which consists of a microporcessor with associated electronics and a radio transciever [Garrett, 1975]. The applications software of the technology consists of a set of novel techniques for dynamic sharing of the communication channels, for efficient and reliable packet transportation, for network initialization and reconfiguration, and techniques for real time diagnosis and control of programs and parameters in the PRU's.

There are three basic functional components of the Packet Radio System: the Packet Radio Terminal, the Packet Radio Station, and the Packet Radio Repeater. The PR Terminal consists of a common type terminal or computer interfacing to a PRU. The Repeater is a stand alone PRU which operates as a relay switching node and provides radio connectivity to interconnect communication devices within the radio net and/or to connect to a gateway into another network. In applications in which terminals are mobile, the Repeater is considered as an area coverage device [NAC, 1974]. The PR Station consists of a minicomputer interfacing to a PRU. The Station performs such functions as PRU initialization, connectivity monitoring, global stability control functions, accounting, buffering, and directory functions for radio communication devices. When the PRNET interfaces with other networks, the Station performs the gateway functions [Burchfiel, 1975].

An experimental PRNET will be extensively tested during 1976 in the San Francisco area. In the present implementation, a PRU has two channels of 100 Kb/s and 400 Kb/s. The low data rate channel is used for communication between a Terminal and a Repeater or

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a Station, and the high data rate channel is used in the Repeater-Station network. The PRU is powered by batteries and can transmit at several power levels resulting in several radio connectivity ranges. The present routing algorithm [Gitman, 1975b] implies a centralized store-and-forwared architecture, in which communication between two terminals proceeds via a station.

3. DESIGN CONCEPTS UTILIZED IN THE CASE STUDY

There are several aspects by which the communication requirements for the case considered differ from those for which the PR technology was developed. Specifically, terminals and hosts are not mobile, terminals and/or hosts are colocated, the PRU or its transciever can be placed on elevated areas, and PRU's have access to (practically) unlimited electrical power sources.

In applying the PR technology one can take advantage of the above observations; the major implications of which will be the following:

1. There is no need to interface each terminal or host computer with a PRU. A PRU can serve as a front-end to several colocated hosts and/or terminals.

2. A PRU can perform two functions simultaneously; operate as a front-end to a set of terminals and at the same time perform the relay functions of a Repeater, providing its throughput capacity is sufficient.

3. The freedom in placing the PRU and the availability of electrical power enables the PRU to have a larger effective transmission range than in general deployment conditions.

It may be of interest to note that other results which may reduce cost and improve performance are available. In the reference, Gitman, 1975a, it is shown that directional antennas at stations may significantly increase PRNET capacity. In Gitman, 1975a, an efficient routing algorithm which enables direct PRU

to PRU packet transportation without the need to go through the Station was proposed. This algorithm is particularly useful for applications of the type considered in which devices are not mobile and in which some of the origination and destination process pairs are on the radio network. The above and other available results are not utilized in this preliminary case study.

The 40 host computers and 109 terminals in the 8000 square miles area for which the PRNET is designed are located in 25 different locations. Two of these locations contain backbone switching nodes which interface to a higher level network. We refer to a location as a node. A node includes a terminal, a host computer, or a combination of terminals and hosts.

The following assumptions and guidelines are used in the design.

1. Only the high data rate of 400 Kb/s will be used by the transcievers. That is, since terminals and hosts are not mobile they will be interfaced to a PRU or Station minicomputer with a hardwired connection.

2. Two assumptions related to the number of ports to which communication devices can interface, are used:

    a. All devices in a node can interface to a PRU.

b. At most 3 devices can interface to a PRU. Hence, if a node contains 4 or more devices, a station is provided. This station does not perform any of the control and initialization functions; its only use is to interconnect the set of terminals and/or hosts, (Radio Concentrator, or Radio front end).

3. We assume three different effective transmission distances for a PRU: 12 miles, 16 miles, and 25 miles. The justification for the long transmission range has been discussed before; however, it appears that this is not a significant cost factor when the reliability (connectivity) requirement is low.

4. From the reliability point of view, the only requirement assumed is that every node must have a radio communication path to both backbone nodes. In the designs presented, no requirement for two (or more) independent radio paths from each node to a backbone node was used. However, in the comparison with conventional designs we state the additional hardware needs and evaluate the costs for such requirements.*

5. The maximum throughput (or the capacity) of a single station PRNET is assumed to be 25% of the channel data rate, namely 100 Kb/s. Analytical results for a single hop network in which PRU's use the non-persistent carrier sense access scheme [Kleinrock, 1975] and for a 2-hop network in which devices use the slotted ALOHA random access scheme [Gitman, 1975a], show much higher capacity

* No reliability analysis is done in this paper. The reader may consult reference [NAC, 1976b] for reliability analysis of PRNET's with one and two stations.

values. On the other hand multihop simulation results with overhead related to mobility demonstrate lower capacity values [NAC, 1976a].

6. It is assumed that all traffic requirements from a node are routed toward a Backbone node and the traffic to each node is routed from the Backbone node. This assumption overestimates the traffic since some of these requirements are local.

4. PACKET RADIO DESIGNS FOR THE CASE STUDY

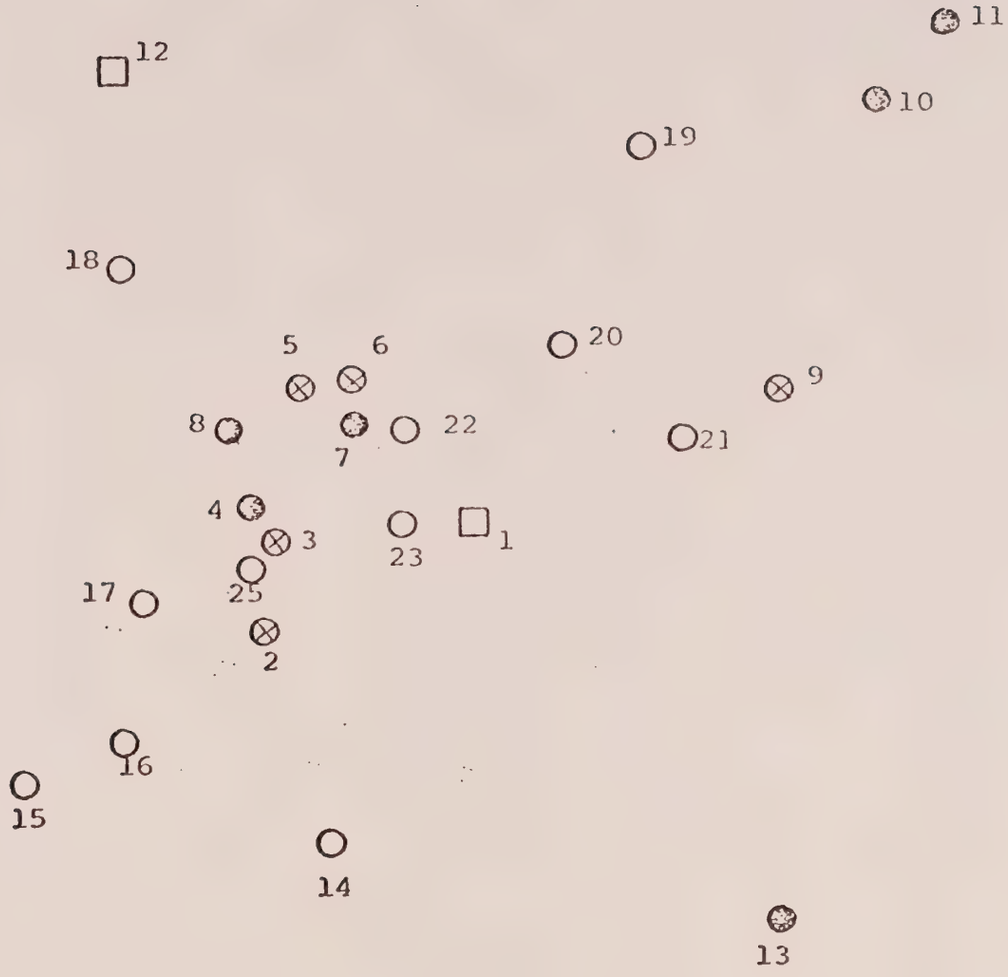
Figure 1 show the location of nodes considered in the case study; the nodes are categorized by the type of devices they contain. In Table 1 we list the number and type of devices that each node contains and the traffic requirements of each node.

The design needs to satisfy capacity requirements and connectivity requirements. It is first noted that the traffic of backbone nodes 1 and 12 need not be satisfied by the PRNET. Second, node 7 has the highest traffic requirement, the total of which (73.13 Kb/s) requires a station capacity. Hence, it is decided to connect node 7 to backbone node 1 with two parallel 56 Kb/s full duplex channels. Furthermore, since there are other nodes in the proximity of node 7, it is not needed for relaying functions and therefore no PRU is provided at its location.

The total traffic requirements of the nodes for which the PRNET is provided is 137.2 Kb/s; thus, at least two PR Stations, at a distance apart which prevents radio interference, are needed to satisfy the traffic requirements.

It was a priori decided to place PR Stations at backbone nodes 1 and 12 and to divide the traffic requirements between them to prevent station saturation. No attempt was made to optimize Station locations although for example, it may have been more economical to provide a station at node 19 and connect node 19 to 12 by a point-to point channel.

Traffic and distance considerations have led to a partition of the nodes between the stations in the following way; nodes 9, 10, 11, 18, 19, 20, and 21 will be served by the station in backbone node 12, and the traffic requirements of all other nodes will be satisfied by the station in backbone node 1. We shall not describe



T	○	TERMINAL(S)
H	⊗	HOST(S)
HT	◉	HOST (S) AND TERMINAL(S)
BN	□	BACKBONE NODE

FIGURE 1: LOCATION OF NODES IN CASE STUDY

ODE	CATEGORY	#H	#T	TRAFFIC IN KB/S (TRANSMIT/RECEIVE) HOST TRAFFIC	TERMINAL TRAFFIC	TOTAL TRAFFIC
1	BN	1	10	29.4 , 24.6	1.303, 8.394	30.703, 32.994
2	H	1		9.85, 0.87		9.85, 0.87
3	H	1		6.8, 0.2		6.8, 0.2
4	HT	2	5	9.61, 5.9	0.82, 3.13	7.43, 9.03
5	H	1		10.4, 2.08		10.4, 2.08
6	H	1		1.33, 0.168		1.33 0.168
7	HT	7	24	40.02, 20.91	1.8, 10.4	41.82, 31.31
8	HT	1	31	2.2, 0.4	0.12, 0.57	2.32, 0.97
9	H	1		5.2, 4.3		5.2, 4.3
0	HT	1	1	13.13, 1.53	0.22, 0.12	13.35, 1.65
1	HT	1	6	12.17, 1.2	0.676, 6.814	12.846, 8.014
2	BN	1		31.24, 24.37		31.24, 24.37
3	HT	1	2	2.5, 0.5	0.007, 0.033	2.507, 0.533
4	T		1		0.004, 0.13	0.004, 0.13
5	T		1		0.002, 0.012	0.002, 0.012
6	T		1		0.29, 1.49	0.29, 1.49
7	T		2		0.22, 1.9	0.22, 1.9
8	T		1		0.004, 0.13	0.004, 0.13
9	T		4		0.18, 0.9	0.18, 0.9
0	T		1		0.004, 0.13	0.004, 0.13
1	T		2		0.006, 0.142	0.006, 0.142
2	T		12		0.059, 0.274	0.059, 0.274
3	T		1		2.7, 2.7	2.7, 2.7
4	T		3		0.13, 0.65	0.13, 0.65
5	T		1		0.22, 0.11	0.22, 0.11

TABLE 1: TRAFFIC REQUIREMENTS OF NODES IN CASE STUDY

the detailed considerations which led to this partition. For example, if nodes 5 and 6 were connected to backbone node 12, the transmissions of nodes 5 and 6 using omnidirectional antennas would in any event interfere with backbone node 1. Furthermore, although (as will be seen) the traffic is not equally divided among the stations, multihop PRNET analysis [GITMAN, 1975a; NAC, 1976c] show that the traffic bottleneck is not always at the station. Specifically, if nodes 5 and 6 were connected to node 19 via node 20 and then connected to the station at backbone node 12 via a string of stand alone PRU's, then the station would not be saturated but the PRU in node 19 and the string of PRU's will all be saturated.

We now present the results of the various designs. Six different designs are made based on the combinations of assumptions 2 and 3. Namely, the effective transmission range of a PRU and the number of ports assumed for hardwired connections of terminals and hosts.

Figures 2, 3, and 4 show the connectivity of the resulting PRNET's for an effective PRU transmission range of 12 miles, 16 miles, and 25 miles, respectively. It is assumed that each node (apart from 7) contains either a PRU or a PR Station. In addition, stand alone PRU's are added for packet relay purposes to provide radio connectivity to a station for communication purposes and to satisfy the requirement that each node has a radio path to both stations (see, for example, PRU 29 in Figure .2). However, one can see that some nodes have only a single path, in particular when PRU transmission range is 12 miles.

It is noted that when one of the stations is down, the remainig station will be traffic saturated if the traffic requirements of nodes are those of the busy hour (the values in Table 1). In such event, flow and stability control algorithms of the station will

limit the input traffic rate of low priority messages. Also note, for example, that PRU 27 in Figure 4 is placed so that there is no radio connectivity between it and nodes 5 and 6, otherwise PRU 27 may become traffic saturated during peak hour conditions.

The solid lines in Figures 2, 3, and 4, show the paths that will be utilized by each node for communication with its primary station. There are also the minimum hop paths to the primary station and from a partition of the nodes between the two stations for message handling. The PRU's in the network will include routing information which will enable them to transport packets to the primary station (and secondary station) along the path shown in the figures [GITMAN, 1975b]. One can see from the above figures that one can model the PRNET as a one or 2-hop network (the Station at node 1) or as a string of Repeaters leading to a Station (the Station at Node 12), for obtaining detailed traffic and delay analysis.

Table 2 gives the traffic rates at the two stations and the effective utilization of the channel at the station PRU. These values are the same for all the designs, since the partition of the nodes between the stations is fixed. Note also that the two stations are connected through a point-to-point network for which they perform the gateway functions. Table 3 gives the quantities of PRU's and Stations for the six designs. The cost of the designs is parametrized and compared with conventional technology designs in the next section. The approximate pairwise distance matrix of nodes is given in Table 4.

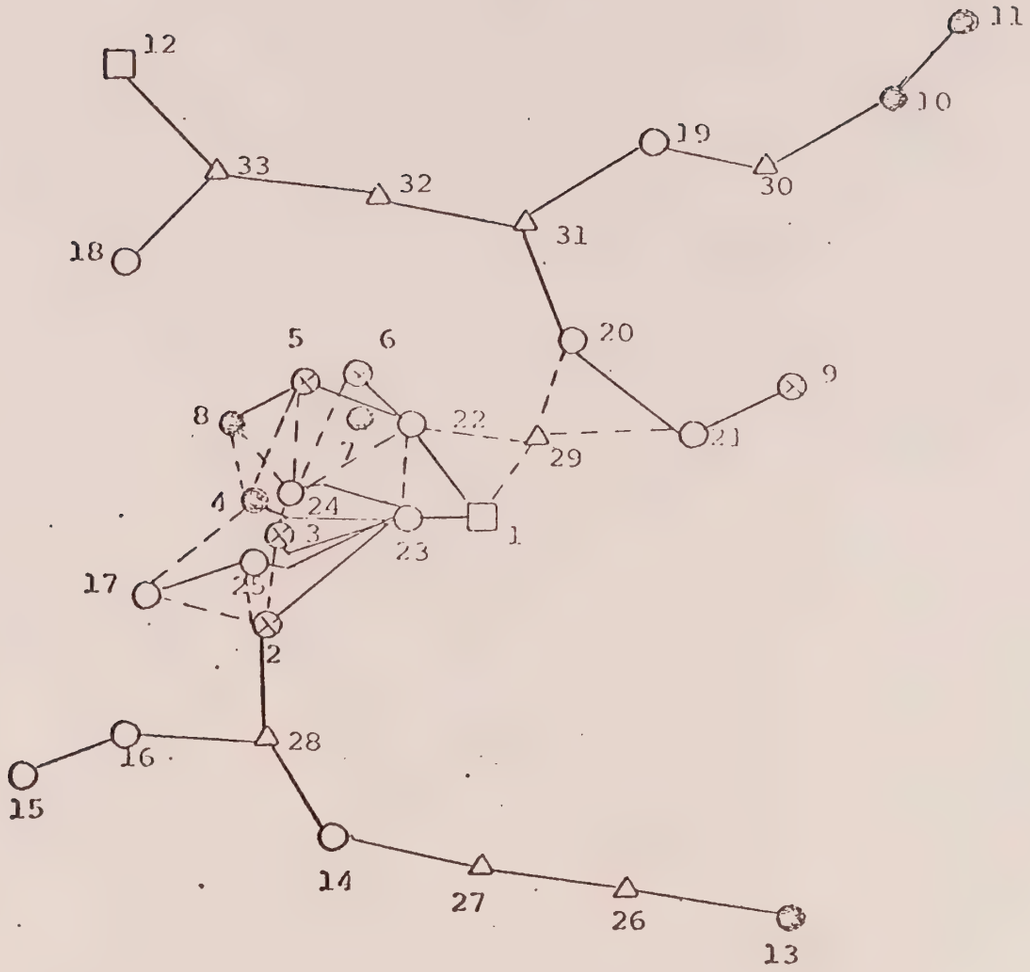
	TRAFFIC TO STATION [Kb/s]	TRAFFIC FROM STATION [Kb/s]	TOTAL TRAFFIC [Kb/s]	EFFECTIVE UTILIZATION OF CHANNEL AT STATION
Station at Node 1	50.4	40.1	90.5	22.6%
Station at Node 12	31.6	15.1	46.7	11.7%

TABLE 2: STATION TRAFFIC LOAD

	PRU TRANSMISSION RANGE [miles]	PRU PORTS	TOTAL NUMBER OF PRU's	TOTAL NUMBER OF PR STATIONS
Design 1	12	No Limit	30	2
Design 2	16	No Limit	27	2
Design 3	25	No Limit	24	2
Design 4	12	3	25	7
Design 5	16	3	22	7
Design 6	25	3	19	7

TABLE 3: HARDWARE QUANTITIES FOR PACKET RADIO NETWORK DESIGNS*

* The station is composed of a minicomputer (presently a PDP 11/45), interfacing with a PRU, as defined in Section 2. Thus, N (PRU's) and M (stations) are equivalent to (N+M) (PRU's) and M (minicomputers) and M (interfaces).

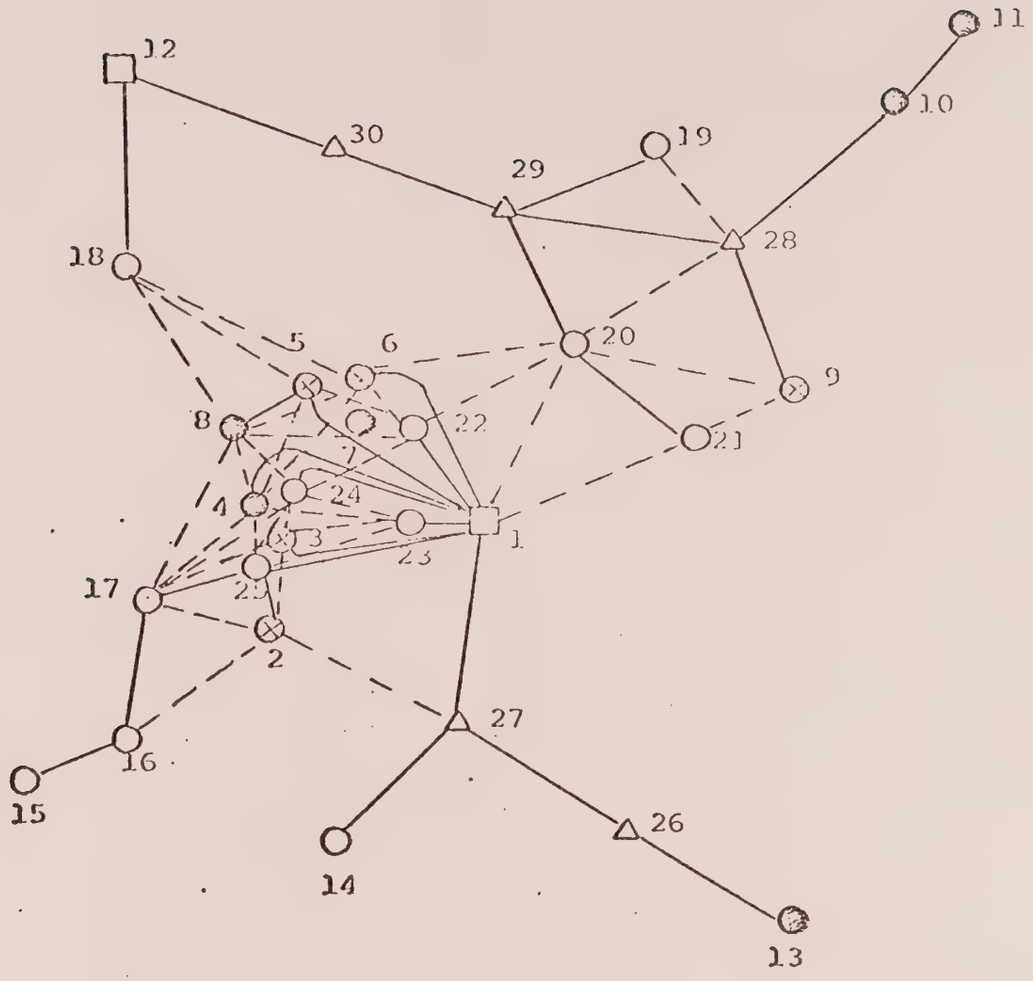


T	○	TERMINAL(S)
H	⊗	HOST(S)
HT	⊗	HOST (S) AND TERMINAL(S)
BN	□	BACKBONE NODE
PR	△	PACKET RADIO UNIT (REPEATER)

——— RADIO LINK FOR ROUTING

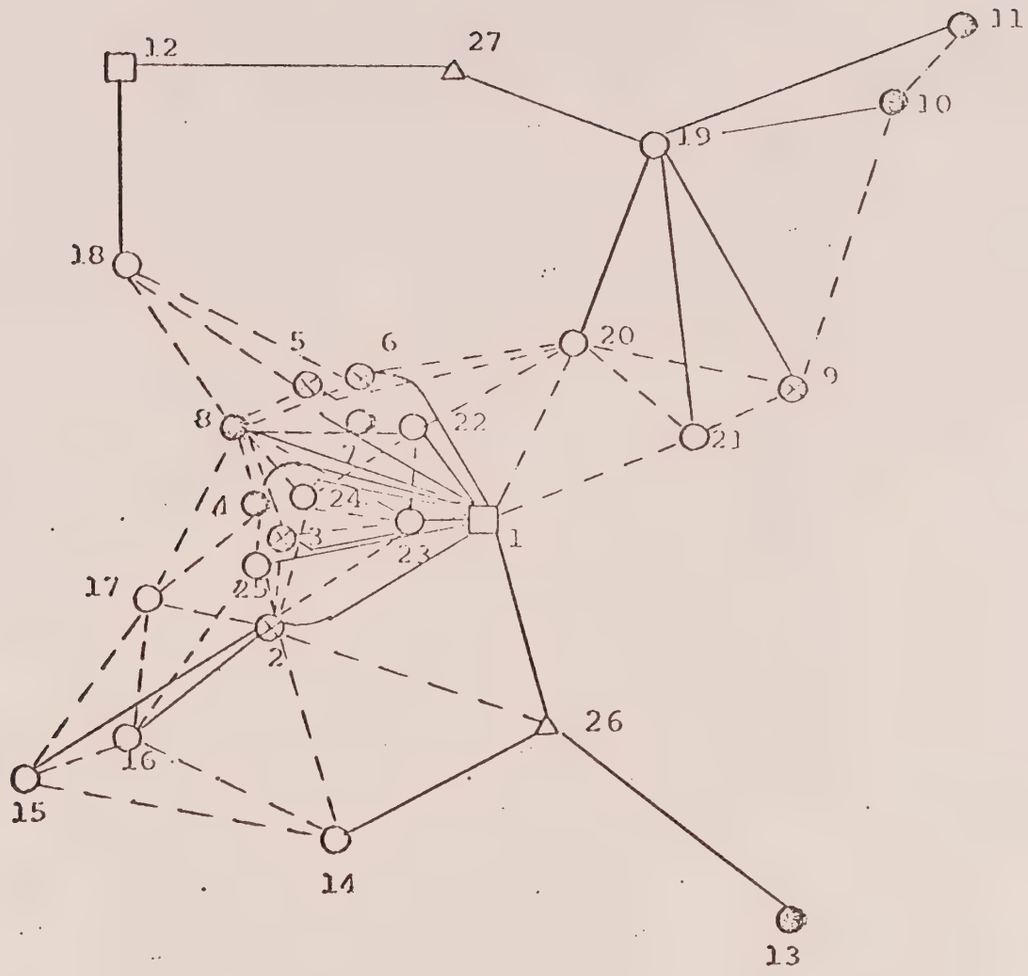
- - - - - - - - OTHER RADIO LINKS

FIGURE 2: PRNET CONNECTIVITY AND ROUTING FOR PRU TRANSMISSION RANGE OF 12 MILES



T	○	TERMINAL(S)	———	RADIO LINKS FOR ROUTING
H	⊗	HOST(S)		
HT	◉	HOST (S) AND TERMINAL(S)	- - - - - - - - -	OTHER RADIO LINKS
BN	□	BACKBONE NODE		
PR	△	PACKET RADIO UNIT (REPEATER)		

FIGURE 3: PRNET CONNECTIVITY AND ROUTING FOR PRU TRANSMISSION RANGE OF 16 MILES



T	○	TERMINAL(S)	——— RADIO LINKS FOR ROUTING
H	⊗	HOST(S)	- - - - - - - - OTHER RADIO LINKS
HT	⊛	HOST (S) AND TERMINAL(S)	
BN	□	BACKBONE NODE	
PR	△	PACKET RADIO UNIT (REPEATER)	

FIGURE 4: PRNET CONNECTIVITY AND ROUTING FOR PRU TRANSMISSION RANGE OF 25 MILES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1		18	14	17	16	14	10	19	25	46	54	46	39	28	41	32	26	26	33	15	16	12	5	14	16
2			7	10	20	21	18	16	44	64	73	48	46	18	23	14	10	32	49	32	35	19	10	10	6
3				3	12	14	11	10	40	58	67	41	50	26	29	20	8	26	43	27	32	14	10	3	3
4					10	13	10	6	42	59	67	38	52	27	28	20	8	22	46	27	33	14	12	3	4
5						4	4	6	36	50	58	29	56	37	39	32	17	16	33	16	29	9	14	10	15
6							4	10	32	46	54	31	54	38	42	34	25	19	29	16	26	5	12	12	16
7								9	33	48	56	34	52	34	39	31	21	21	32	17	26	4	9	8	13
8									42	56	65	31	58	35	33	26	16	16	39	26	35	14	15	8	10
9										25	31	57	43	51	67	58	52	52	22	16	65	28	31	39	43
10											8	58	67	74	87	78	70	59	18	30	31	39	50	56	60
11												64	74	83	95	86	78	66	25	39	39	53	58	65	69
12													85	65	58	55	44	16	39	41	52	37	43	37	41
13														35	59	52	54	73	64	49	39	49	43	50	49
14															23	17	25	50	62	45	43	34	27	27	24
15																9	17	42	70	54	58	41	35	31	26
16																	12	38	63	47	50	31	27	22	18
17																		27	53	38	44	21	21	19	10
18																			41	33	44	26	30	23	26
19																				17	24	29	35	39	44
20																					12	14	18	26	29
21																						21	7	11	16
22																							8	11	16
23																								9	12
24																									5
25																									

TABLE 4: APPROXIMATE PAIRWISE DISTANCE MATRIX IN MILES

2.5 COST COMPARISON OF CONVENTIONAL AND PACKET RADIO TECHNOLOGIES

Six PRNET designs and two designs using a conventional technology are compared in this section. The cost figure associated with a design is the monthly cost. Cost factors for the conventional designs are based on current procurement estimates for tariffed communication lines and hardware. The hardware cost factors (for both technologies) include purchases price, installation cost (20% of base price), initial support costs (67% of base price), operations and maintanance costs (47% of base cost over 10 years), and amortization over a 10 year period with 10% yearly interest.

The cost of the PRNET designs are derived as a function of the unit price cost of a PRU. Rather than having two unit cost variables, one for the PR Station and one for the PRU, the Station hardware cost is decomposed into the cost of the minicomputer PDP11/45 with an ELF operating system and 64K of core, plus the cost of a PRU (assumed together with its interface). The purchase price of the station minicomputer used in the study is $62,200*. For example, the total monthly cost of PRNET Design 1, assuming $10,000 purchase price per PRU is $28,873. The monthly costs for the various hardware components of this design are shown in Table 5.

Two conventional minimal cost designs for the same set of computers, terminals, and backbone nodes, are used for comparison. Such designs assume the use of communications equipment (TDMX, concentrators, or terminal controllers) to merge the requirements of colocated terminals; when cost effective. Table 6 gives the hardware costs, line costs and total monthly costs for the conventional designs. The two designs are defined as follows:

Design C1: Each node is connected to the nearest backbone node.

* It was assumed that the cost of the PR Station is the same as the cost of a concentrator based on the same minicomputer and contains 32K of core, 64 I/O ports for low and medium speed lines, time division demultiplexing by software, and a high speed line interface to a Host computer.

Design C2: Dual homing; each node is connected to both backbone nodes.

Figure 5 shows the total system monthly cost for all the designs as a function of the purchase price for a PRU. It is not clear with which of the designs using conventional technology should the PRNET designs be compared. It is apparent that the PRNET designs are more reliable than Design C1, since all the nodes have radio paths to PR Stations in both backbone nodes, and routing algorithms which enable each node to communicate with both stations are available. However, PRNET desings provide less reliability than Design C2, because one PR station cannot handle all the traffic during the busy period; furthermore, the number of hops for some of the nodes when communicating with a single station is large.

Comparing PR and conventional technologies, one can see that the PR technology is more economical when the PRU purchase price is less than $6,000 (the cost of all PRNET designs is smaller than both conventional designs). For a PRU cost of less than $20,000, the cost of all PRNET designs are less than conventional Design C2 but some are more costly than Design C1.

Comparing the various PRNET designs shows that the total cost is not very sensitive to the different assumptions of PRU effective transmission range when PRU cost is low (say less than $12,000). This, however, is due to the particular node distribution in the case study under consideration and the requirement that a single radio path for each node is sufficient.

To upgrade the reliability of PRNET designs to that of Design C2 it would be necessary to add several PRU's for radio connectivity, to increase backbone node capacities by using directional antennas, or to add another station in the area which does not interfere with the other stations and connected to both backbone nodes via point-to-point channels.

It is estimated that for upgrading the reliability of the PRNET designs to that of the dual homing conventional design C2 it would be necessary to add 5 and 15 PRU's for a PRU transmission range of 25 and 12 miles, respectively. Furthermore, it is assumed that directional antennas are used in the backbone nodes to increase the capacity.

Figure 6 shows a comparison of Design C2 with the upgraded PRNET designs. The PRNET designs are for the two different assumptions of the number of ports per PRU and PRU transmission ranges from 12 to 25 miles. One can see that all the PRNET designs are more economical than the conventional designs for a PRU purchase price of $15,000 or less. For a PRU purchase price of $20,000 or less PRNET designs are more economical if the PRU transmission range is 25 miles or if a PRU has a large number of ports.

	PURCHASE PRICE [$]	NUMBER OF UNITS	MONTHLY COST PER UNIT [$]	TOTAL MONTHLY COST [$]
Station Minicomputer	62,200	2	2,724	5,448
Concentrator at Node 7	62,200	1	2,724	2,724
Line Costs Node 7 - Node 1 56 Kb/s		2	972	1,945
PRU	10,000	32	585	18,720

TABLE 5: SAMPLE EVALUATION FOR PRNET DESIGN 1, ASSUMMING PRU PURCHASE PRICE OF $10,000.

	TDMX MONTHLY COST [$]	CONCENTRATOR MONTHLY COST [$]	TERMINAL CONTROLLER MONTHLY COST [$]	TOTAL HARDWARE MONTHLY COST [$]	MONTHLY LINE COST [$]	TOTAL MONTHLY SYSTEM COST [$]
Design C1	636	3 x 2, 724	1,170	9,978	23,387	33,365
Design C2	967	3 x 2, 724	1,170	10,309	48,942	59,251

TABLE 6: MONTHLY COST OF CONVENTIONAL DESIGNS

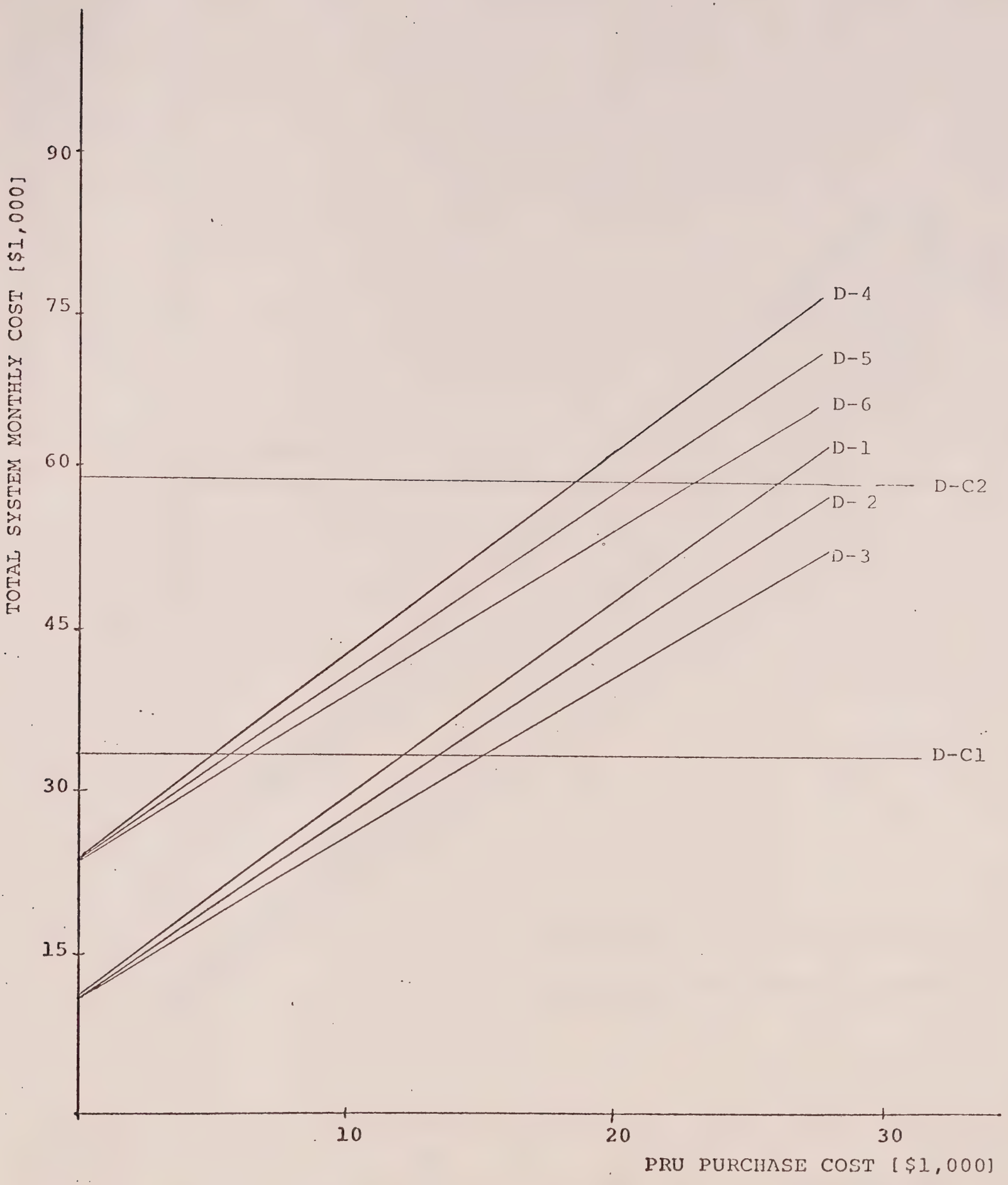


FIGURE 5: MONTHLY SYSTEM COST FOR ALTERNATIVE DESIGNS

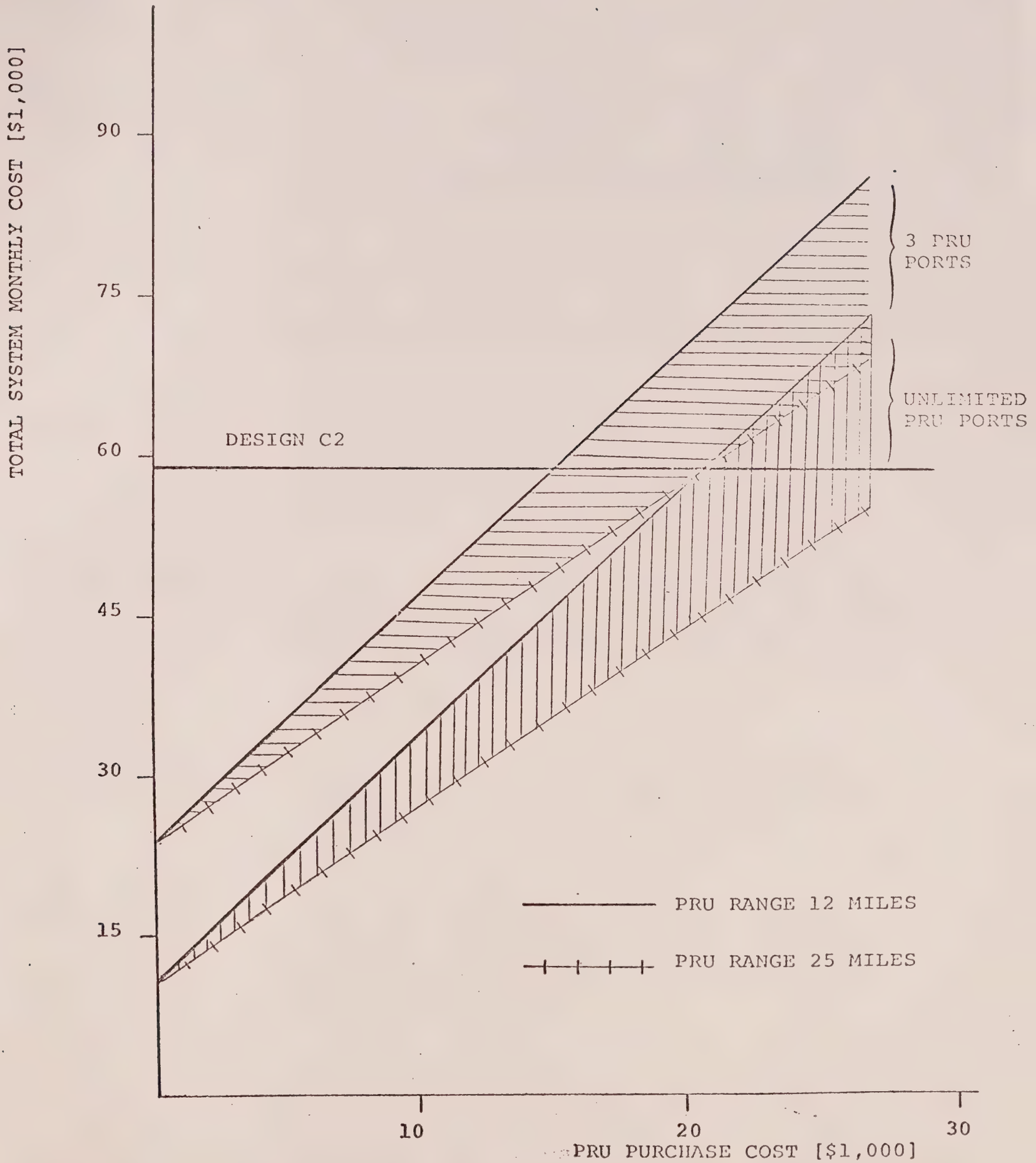


FIGURE 6: MONTHLY SYSTEM COST FOR ALTERNATIVE DESIGNS WITH DUAL HOMMING RELIABILITY

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